ARMY RESEARCH LABORATORY

Practical Aspects of Numerical Simulations of Dynamic Events: Effects of Meshing

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Abstract

The use of finite-difference and finite-element computer codes to solve problems involving fast, transient loading is commonplace. A large number of commercial codes exist and are applied to problems ranging from fairly low to extremely high damage levels (e.g., design of containment structures to mitigate effects of industrial accidents; protection of buildings and people from blast and impact loading; foreign-object impact damage; and design of space structures to withstand impacts of small particles moving at hypervelocity, a case where the pressures generated exceed material strength by an order of magnitude). But, what happens if code predictions do not correspond with reality? This report discusses various factors related to the computational mesh that can lead to disagreement between computations and experience. Subsequent reports will focus on problems associated with contact surfaces and material transport algorithms, constitutive models, and the use of material data at strain rates inappropriate to the problem. It is limited to problems involving fast, transient loading, which can be addressed by commercial finite-difference and finite-element computer codes.

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1. Introduction

This report focuses on the numerical simulation of problems in mechanics involving fast, transient loading. For practical purposes, these can be divided into problems involving structural dynamics and wave propagation (Table 1). There is no clear demarcation between these two areas. The labels are misleading since both types of problems involve wave propagation. Nonetheless, these designations have caught on in the literature. These two labels deal with the behavior of inert materials that are subjected to intense impulsive (distributed over a surface, such as air blast, over a long time [milliseconds to seconds]) or impact (applied to a single point or a very small area over a very short [nanoseconds to microseconds] time span) loading.

There is also a large class of energetic materials that reacts quite differently when excited. Energetic materials are not discussed in this report. For more information on this topic see Zukas and Walters [1], Cooper [2], Cooper and Kurowski [3], Cheret [4], Blazynski [5], Fickett and Davis [6], and Mader [7, 8].

Most of the work done in the area of fast, transient loading is experimental in nature. This is due either to complexities of geometry or the nonlinearity of material behavior or both. Closed-form analytical solutions are generally rare and apply only to some small subset of the overall problem.

Numerical solutions, in the form of finite-difference and finite-element codes, have been successfully used in the past. In particular, the combination of experiments, numerical solutions, and dynamic material characterization has been shown to be very effective in reducing both manpower requirements and cost [9]. However, the computer codes available for dynamic analyses are quite complex. Considerable experience with both the codes and the physical problems they are intended to solve is vital. Also critical is the determination of material constants for the various constitutive models available at strain rates appropriate to the problem.

Table 1. Dynamic Situations

STRUCTURAL DYNAMICS
• Blast/Shock Loading of Structures • Underwater Explosions • Fluid-Structure Interactions • Mechanical System Dynamics - machinery & mechanisms - agricultural, construction, off-highway equipment - turbomachinery systems - containment structures - vehicular collisions - aeronautical/aerospace systems • Biodynamic Systems • Plate and Shell Structures • Nonperforating Impacts • Rotating Machinery • Metal Forming
WAVE PROPAGATION
• Lunar/Planetary Impact • Explosive Welding, Forming, Compaction • Shock Consolidation/Shock Synthesis • Chemical Energy Penetrators - explosively formed penetrators (EFP) - shaped charge jets • Kinetic Energy Penetration - fragments - long rods - bombs

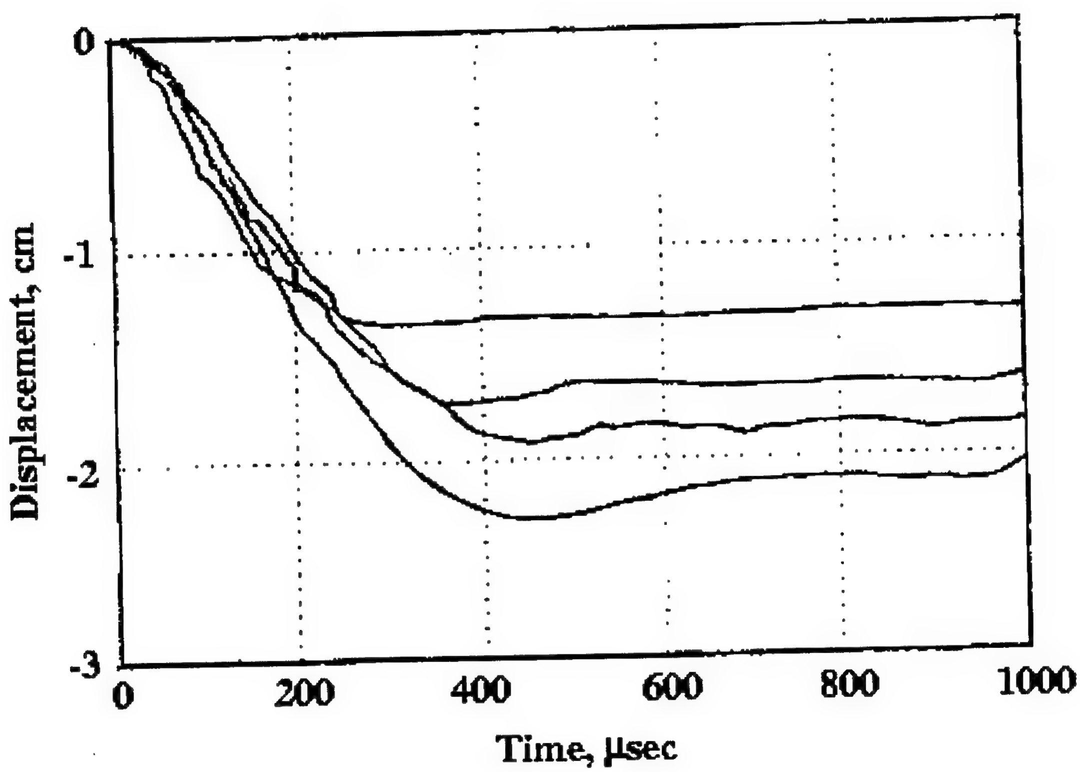
Figure 1 shows the dramatic effect that experience can have on computed results. The figure, provided by Dr. Paul Senseny of the former Defense Special Weapons Agency (now called Defense Threat Reduction Agency), shows the results obtained by four different users of the DYNA code for a problem involving airblast loading of a silo door. Each of the code users worked independently. Note that four people with four different backgrounds produced four distinctly different results with the same code in solving the same problem.

Why this emphasis on experience? To be sure, experience is not a sufficient factor to guarantee accurate computations. Indeed, all four code users in the previous problem could have been experienced in some sense. But experience is an important factor. There exist many cases in computational continuum dynamics where tradeoffs must be made to achieve reasonable results in a reasonable time at finite costs. Szabo and Actis [10] point out the importance of timely solutions in industry. Quoting from an engineer's experience at a major industrial laboratory, they point out that "...the stress engineer may not be able to guide the design because by the time he has generated his several thousand degree-of-freedom finite-element model, prototypes are already being made." Anyone can perform finely resolved one-dimensional (1-D) calculations almost by rote. Two-dimensional calculations (2-D), though now largely performed on workstations and personal computers, require a keen knowledge of the problem and numerical simulation methods. This holds even more for successful three-dimensional (3-D) simulations that, with all their compromises, will still be expensive and require significant computer resources.

2. Difficulties Inherent in Numerical Approximations

When a user acquires a code, he/she receives a package in which certain decisions have been made by the developer. The user has no control over some of the approximations that come as part of the package but must be aware of them, as they will affect all solutions that the user will generate with the package. This section briefly describes these errors and cites sources in the finite-difference/finite-element literature where extensive discussions can be found. These are problems inherent in transforming a physical problem into a discrete model and solving it on

The Same Code Will Produce Different Answers
In The Hands of Different Users



DYNA was used in all calculations

Figure 1. Variation of Computational Results With User Experience.

computers with limited precision through the medium of finite differences and finite elements. Each difference scheme and each element have unique characteristics that can affect the numerical solution. For example, most implicit schemes for advancing the solution in time have a certain amount of viscosity built into them over which the user generally has no control. Yet, the user must be aware of this characteristic when he/she sees his/her numerical solution drift out of phase with an experimental or analytical result. Certain finite elements are prone to locking (becoming excessively stiff) when the constitutive relationship is evaluated at element Gauss points. This can be overcome by evaluating the constitutive equations at one point (usually the element centroid). This procedure is called "underintegration." It eliminates locking but gives rise to spurious deformation modes known as "hourglassing." A user, unaware of this, might interpret such numerical noise as a physical response. Explicit integration schemes are only conditionally stable. Using stability fractions built into explicit hydrocodes without consideration of the problem being solved can lead to unstable solutions that can degrade over hundreds of cycles and could be interpreted by novice code users as a physical response of the system being modeled.

The errors inherent in finite-element modeling are nicely discussed by Utku and Melosh [11], as are guidelines for mesh preparation by Melosh and Utku [12]. A superb work on practical aspects for static and dynamic finite-element analyses is the book by Meyer [13]. Extremely valuable insights into finite-element design and its practical application are to be found in MacNeal's book [14]. Morris and Vignjevic [15] review error control and error bounding methods for finite elements. They also present a method for error control in the idealization phase of a full finite-element analysis. These, together with personal experience, are the main references for the material in this section.

An analyst begins by examining some physical problem that needs to be modeled numerically. This may be necessary because it is too expensive, too difficult, or just plain impossible (as in nuclear testing) to perform parametric experiments. It might be because the information needed does not lend itself to direct measurement. It is often the case [9, 16] that the combined use of experiments and calculations, including some material characterization at high strain rates, produces more information in less time and at less cost than reliance on experiments or calculations alone.

At first glance, a problem may appear to be extremely complex. Pressure vessels come with various cutouts, end caps that can range from circular plates through hemispherical shells, pipes coming in and out, some irregular sections, weld points, and a countable infinity of bolts and assorted restraining devices. Face it, real structures are messy to model numerically. They can be mounted to floors and walls and receive and transmit loads to these through a variety of mounts (shock isolation is popular in Japan and other earthquake-prone areas). The space shuttle has a nice, clean shape, but most space structures tend to show greater similarity to the highly irregular surfaces of the space cruisers in Star Wars than to the shuttle. Thus, high-velocity impact-generated debris and ricocheting projectiles can interact with critical, externally mounted equipment such as antennas and solar panels.

Three-dimensional impact problems are the rule rather than the exception. Uniform grid resolution is generally not possible in practical problems. Some gradation of the mesh is required. If this is not done with great care, spurious signals and assorted numerical artifacts arise in the calculation, leading to instabilities or a masking of the desired results. Even coarse calculations can require in excess of 40 central processing unit (CPU) hours on modern computers. If sufficient memory is not available to run the problem "in-core," then extensive buffering between main memory and mass storage is required, further increasing turnaround time and cost. For sufficiently large problems on a small central memory machine, it is possible to approach situations where the bulk of CPU time is spent on input-output operations and only a small fraction is spent in advancing the solution, rendering the computation uneconomical.

Does this mean that 3-D calculations cannot be done today? Not at all. Quite a few practical problems have been successfully addressed with 3-D codes. However, compromises are required, and these, in turn, require a keen understanding of the physical problem, the effects of discretization on that problem, and the effects that numerical artifacts (such as uneven resolution in different coordinate directions, mixing of implicit and explicit integration schemes or explicit-explicit partitions, choice of mesh or element type, effects of sliding surfaces or interfaces, and the use of various viscosities to stabilize computations) have on the solution.

All the details and materials in a real structure usually cannot be accounted for in a numerical simulation. Hence, the analyst must now make an analytically tractable model without sacrificing the essential elements that make up the response of the physical structure. The first order of business is to simplify the physical system by taking all essential geometric and material features that govern its response into account. Some simplification of geometry and lumping of masses is inevitable. Depending on the situation, one may be able to employ specialized mathematical models such as beam, plate, or shell theory (or a combination of these). Preliminary analyses need to be made to determine whether large strains and rotations constitute a part of the response or whether a linear analysis will suffice. A number of uncertainties are introduced in this process, some of which cannot be quantified. Other uncertainties are due to variabilities in material properties, loading, fabrication, and other factors. For example, rolled homogeneous armor (RHA) steel is used extensively in military construction. It can safely be said that RHA is rolled. It is also used as armor. However, the military specifications that govern the production of RHA have wide tolerances so that it is anything but homogeneous. Material properties (primarily hardness) are known to vary by as much as 10% within a lot of RHA and up to 30% from lot to lot. This makes single tests (the famous "one-shot statistics") useless and correlation between numerical results and experiments unlikely unless a statistically meaningful number of tests have been done. Simple go/no-go ballistic tests can cost upward of $2,000 each. Instrumented field tests can run from $10,000 to $100,000 each. As a rule, then, a statistically significant data set is almost never available.

3. Idealization

The ultimate goal of this idealization process—the transition from a complex physical model to a simpler one but incorporating all the relevant physics—is a mathematical model consisting of a number of equations that closely represent the behavior of the physical model. A formal seven-step process was proposed by Morris and Vignjevic [15]. An experienced analyst will go through the procedure guided by a few principles and much insight garnered over a long career. The time required might take weeks to months, depending on the complexity of the physical system and the accuracy required in the analysis. If the assumptions of the mathematical model are reasonable, very

little mathematical modeling error results. If this is poorly done, say if the height-to-span ratio of beam theory is violated, the thickness-to-radius ratio for thin shells is not satisfied, a poor choice of material properties is made, or the constitutive model omits a critical item such as dynamic failure, serious errors can be incurred. Such synthesis is not taught in schools but learned in apprenticeship with an experienced modeler. Fortunately, in the vast majority of cases, this is done very well so that mathematical modeling errors are negligibly small, or at least smaller than errors committed by code users, the topic of the next section.

A solution is needed for the mathematical model. Since most problems involving high-strain-rate loading are not analytically tractable, recourse is made to a computer. In the process of computing, especially in matrix operations, situations occur where differences between numbers of almost equal magnitude must be taken. This can lead to situations where the roundoff error can completely overwhelm the computed quantity. Given a machine, there is always a limit to the mesh refinement beyond which computed quantities may be 100% erroneous [11]. Roundoff errors may be kept negligibly small by using "...longer wordlength machines and double precision arithmetic with not too refined finite element meshes" [11].

Most dynamic analyses for problems involving wave propagation are done with the simplest elements—constant or linear strain triangles and quadrilaterals in 2-D computations, tetrahedra and hexahedra in 3-D computations. Many early (mid-70s) finite-element codes, such as Lawrence Livermore National Laboratory's DYNA and DYSMAS-L, incorporated high-order elements in their initial formulations. With experience, these were dropped. Many transient response calculations in the wave propagation regime involve the presence of steep stress gradients and shock waves. It has been found with experience that there is marginal increase in accuracy but considerable increase in cost in trying to model what are essentially discontinuities with higher order polynomials. The characteristics of these elements, and the problems of locking and reduced integration associated with them, are lucidly discussed in the book by MacNeal [14]. The original literature and the code manuals should also be reviewed in order that these elements not be misused.

Code users should also be aware of the viscosity built into implicit temporal integrators and the conditional stability of explicit integrators. Additional information can be found in Belytschko and Hughes [17], Donea [18], and Zienkiewicz [19].

4. The Human Factor

It is generally accepted that, if the idealization from physical system to mathematical model is done well, the errors due to truncation, roundoff, and other properties of finite-element or finite-difference schemes can be readily detected and contribute to no more than about 5% of the total solution error. Solutions, however, can be totally invalidated by poor choice of mesh, failure to include relevant physics in the constitutive description, using a limited or inappropriate database to evaluate the constants of a constitutive model, failure to recognize instabilities, or the effects of contact surfaces on numerical solutions. In short, computational techniques come with certain built-in limitations that are easily recognizable and, with few exceptions, controllable. To really mess up requires a human.

Some, but hardly all, of the errors in the application of computer codes to practical problems involve the following.

> <u>Meshing</u>: A code user has available a wide choice of elements in any commercial code. Having selected one or more, the user can then vary element aspect ratio, the arrangement of elements or element groups, choose uniform or variable meshing, and even introduce abrupt mesh changes. All of these will influence the solution to some degree.

> <u>Constitutive Model</u>: Assuming an appropriate model has been selected to account for material behavior under high-rate loading, criteria for material failure, and descriptions of post-failure behavior, the problem of selecting values for the various material constants in the constitutive model remains. These must be selected from experiments conducted at strain rates appropriate to the problem. In many cases, data may not be available. This is

particularly true for situations involving material failure. The estimation of these factors then depends on the skill, knowledge, and experience of the user, and computed results will vary accordingly.

Contact Surfaces and Material Transport: Lagrangian codes incorporate a wide variety of algorithms to account for contact-impact situations. Eulerian codes have a variety of methods for determining the transport of material from one cell to another. Each algorithm uniquely affects the solution. Some codes have incorporated a variety of algorithms and allow the user a choice. The burden is then on the user to choose wisely, and this cannot be done without a knowledge of how the various algorithms affect the solution of both global (e.g., displacements) and local (e.g., strain) variables.

Shortcuts: Because of the expense involved in 3-D calculations, recourse is sometimes made to plane-strain solutions. These are 2-D approximations of 3-D phenomena. Sometimes they produce excellent results, sometimes disasters.

This report focuses on problems involving meshing. Subsequent reports will address the other topics.

5. Problems Related to Computational Meshes

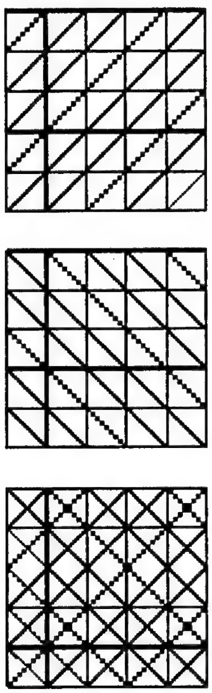
Theoretically, the ideal mesh is uniform in all coordinate directions and "converged" for the critical variable for the problem; that is, it is small enough to give accurate results so that further refinement dramatically runs up the cost of computing with negligible improvement in accuracy. In practice, especially when performing 3-D calculations, this goal is impossible to achieve. Compromises must be made, and the educated analyst must know what effect these compromises have on the numerical solution to his/her problem. In short he/she must know the physical problem and understand how compromises to the computational mesh affect the solution.

There are a number of factors that affect mesh integrity. These include element aspect ratio, element arrangement, uniform vs. graded meshes, and abrupt changes in meshes. Each is now looked at in turn.

5.1 Element Aspect Ratio. Ideally, calculations would be done with 1:1 aspect ratios in the elements. This hardly ever happens in practical 2-D and 3-D calculations. Thus, it would be nice to know how the solution is affected when elements with aspect ratios exceeding 1:1 are used. Creighton [20], using the EPIC-2 code, looked at the effects of aspect ratio, artificial viscosity, and triangular element arrangement on elastic and elasto-plastic impact situations. EPIC uses constant-strain triangular elements that can be arranged in a number of ways. The possibilities included in Creighton's study are shown in Figure 2. The elastic calculations were performed for a steel bar with length-to-diameter (L/D) ratio of 100 striking a rigid barrier at 3.048 m/s. Numerical solutions were compared with an exact solution by Skalak [21], Figure 3, which takes into account the effects of radial inertia. Calculations were performed with one (400 elements), two (1,600 elements), and three (3,600 elements) crossed triangles (four triangles per quadrilateral) across the radius of the bar (length, L = 12.7 cm; diameter, D = 0.254 cm). All calculations were done with an aspect ratio of 1:1. The axial force in the rod as a function of position was compared with Skalak's solution at various times.

As expected, the results show the grid acting as a frequency filter. As the grid is resolved, more and more ringing is computed behind the wavefront. Enough high-frequency components are accounted for in the 3,600-element calculation to compare very favorably with the analytical solution.

Holding the number of elements across the bar radius at three, the element aspect ratio was now increased from 1:1 to 4:1. Again, the filtering characteristics of the mesh is clearly shown. High-frequency components are gradually suppressed until, with the 4:1 mesh, only the ringing directly behind the wave front remains (Figure 4).



(a) IDIA = 1 Hypotenuse of the triangle is drawn from the lower left hand corner to the upper right hand corner.

(b) IDIA = 2 Hypotenuse of the triangle is drawn from the upper left hand corner to the lower right hand corner.

(c) Quadrilateral elements comprised of four triangles.

Figure 2. Element Orientations in the EPIC-2 Code.

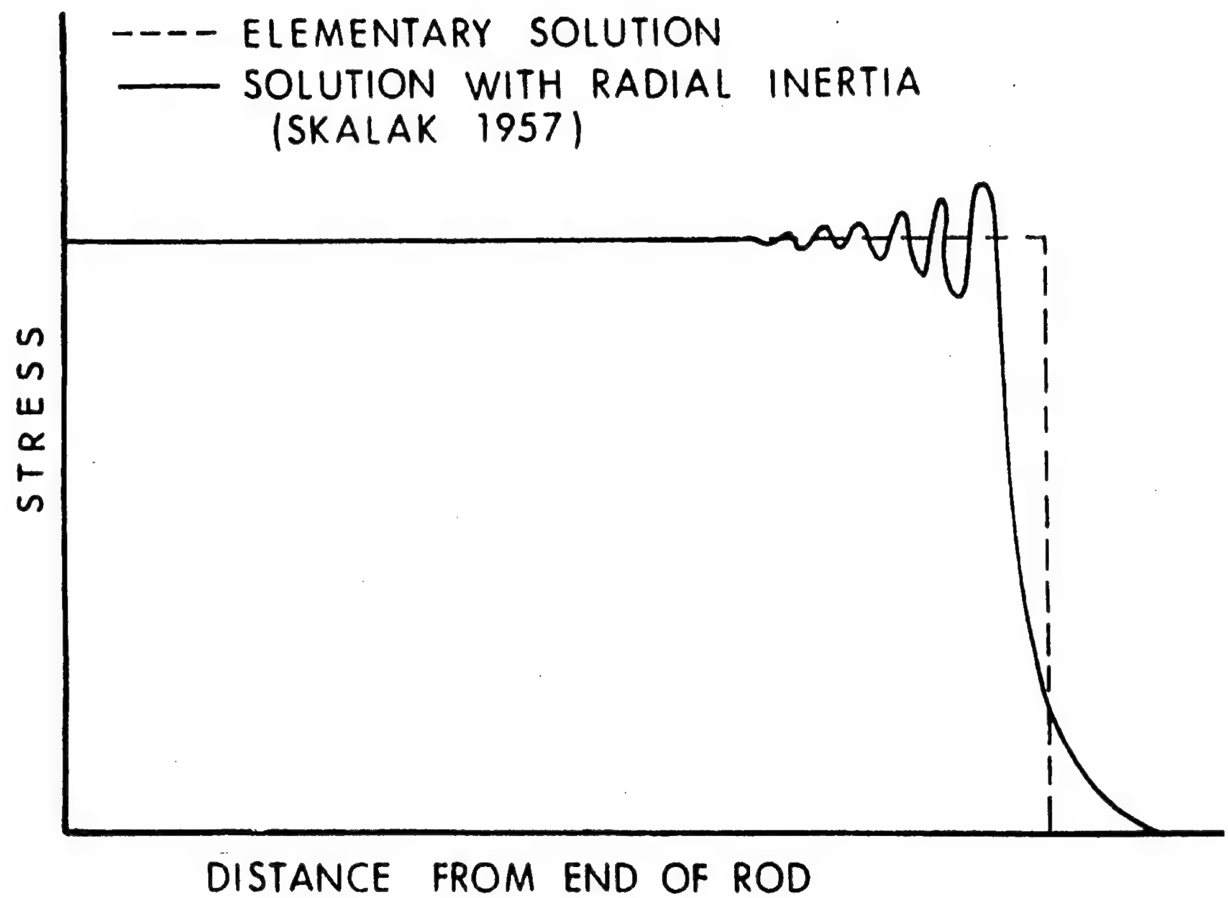


Figure 3. Comparison of Elementary and Skalak Solutions for Bar Impact (Skalak Solution Is Drawn Freehand).

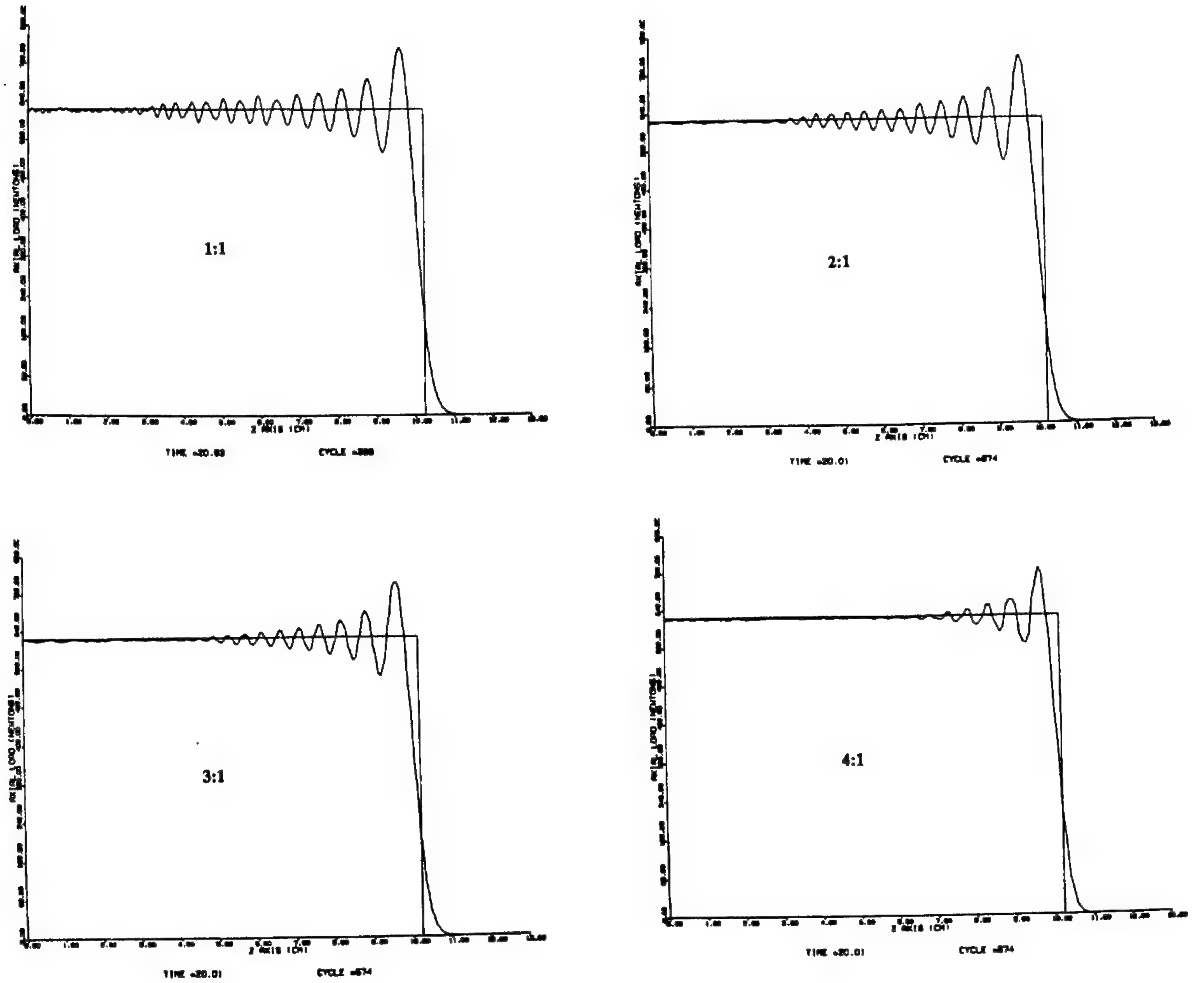


Figure 4. Signal Filtration With Mesh Aspect Ratio.

5.2 Element Arrangement. The arrangement or mixing of elements within a computational mesh can be a problem. Figure 2 shows three possible arrangements of triangular elements. This aspect of mesh generation was also investigated [20]. The specific problem considered was the impact of a steel sphere with a 5.08-cm-thick aluminum target at a velocity of 1,524 m/s. The two-triangle orientations (Figure 2[a] and [b]) gave rise to asymmetries in the calculation. Depending on the orientation of the diagonal, results were either too stiff or too soft. Optimal performance was achieved using the four-triangles-per-quadrilateral grouping (Figure 2[c]). Similar results had been obtained by Zukas [22]. The definitive study on element arrangement for accurate elasto-plastic solutions was done by Nagtegaal et al. [23].

Johnson and coworkers [24, 25] observed that, for 2-D triangular elements, accuracy is much improved if the elements are arranged in a crossed-triangle (four triangles within a quadrilateral) arrangement or if a single average pressure is used for each group of two adjacent triangles (two triangles within a quadrilateral). In three dimensions, Johnson et al. [25] performed a number of simulations using configurations of 6 tetrahedral elements within a brick, 6 tetrahedral elements per brick using a single average pressure for all 6 tetrahedra, as well as an arrangement of 24 tetrahedral elements per brick. This latter case, though the most costly configuration, was expected to produce the best results since the asymmetries present in the six tetrahedra arrangement would be absent. It was also expected that the six tetrahedra configuration with pressure averaging would perform better compared to the six tetrahedra configuration using individual element pressures due to the reduction in the number of incompressibility constraints [23]. Some test cases were compared to experimental data [26]. Between 37,000 and 39,000 elements were used for these calculations of an L/D = 10 tungsten rod striking a 2.5-cm steel plate at normal incidence with a velocity of 1,520 m/s. The case of the six tetrahedra without pressure averaging produced the closest correlation with experiment for residual velocity and the worst for residual rod length. Furthermore, there was indication of locking in the target grid. The closest correlation for rod residual velocity and residual length was achieved for the symmetric 24 tetrahedra per brick arrangement. However, in all cases, including a 2-D calculation, EPIC tended to overpredict residual length by about 16%. This could be due to a number of factors not necessarily related to the grid.

A number of papers present comparisons of plastic strain profiles for Taylor cylinder impacts—the impact of a deformable, short cylinder (L/D < 3, generally, although longer rods have been used) striking a rigid surface at impact velocities under 100 m/s. Johnson [24], for example, compares DYNA, NIKE, and EPIC-2 results with various arrangements of triangles (Figure 5). Many more papers have since appeared to not only test element formulations and arrangements but constitutive relations as well. Such results are interesting but tend to show only minor differences for the various cases considered. It is now clear that the Taylor cylinder is not a very sensitive measure of element arrangement effectiveness. Neither is it a good discriminant for testing constitutive models.

5.3 Uniform and Variable Meshes. The effects of mesh size on wave propagation problems can be seen in Figures 6 and 7. These depict the impact of a long S-7 tool steel rod (L/D = 10, hemispherical nose, D = 1.02 cm) into 2.56-cm-thick RHA plate at 1,103 m/s. The characteristic lengths of this problem are the target thickness and projectile radius. For good results, there should be at least three elements across the radius of the rod. Since uniform mesh spacing is the ideal, this governs the number of elements to be used in the projectile and target.

Figure 6 shows initial grids and results at 50 ms after impact. One, three, and five crossed-triangle meshes were used across the projectile radius for the coarse, medium, and fine cases, respectively. The target grid was then set by requiring a 1:1 aspect ratio of all elements in the calculation. The coarse grid computation shows some anomalies near the projectile-target interface and a v-shaped crater, indicative of numerical difficulties with triangular elements. The other two calculations (Figures 6[d] and [e]) appear to be reasonable. The experimentally determined projectile residual mass was 32.1 g, and the residual velocity was 690 m/s. The computed residual masses were 29 g, 36 g, and 37 g for the coarse, medium, and fine grids, respectively, while the residual velocities were 600 m/s, 670 m/s, and 680 m/s. Coarse zoning is adequate for "quick and dirty" scoping calculations or to get preliminary estimates of global quantities such as length loss in the rod, approximate hole size, residual velocity, and overall deformed shapes of the two solids. It is, however, inadequate to resolve strain and pressure fields with any degree of accuracy. If the

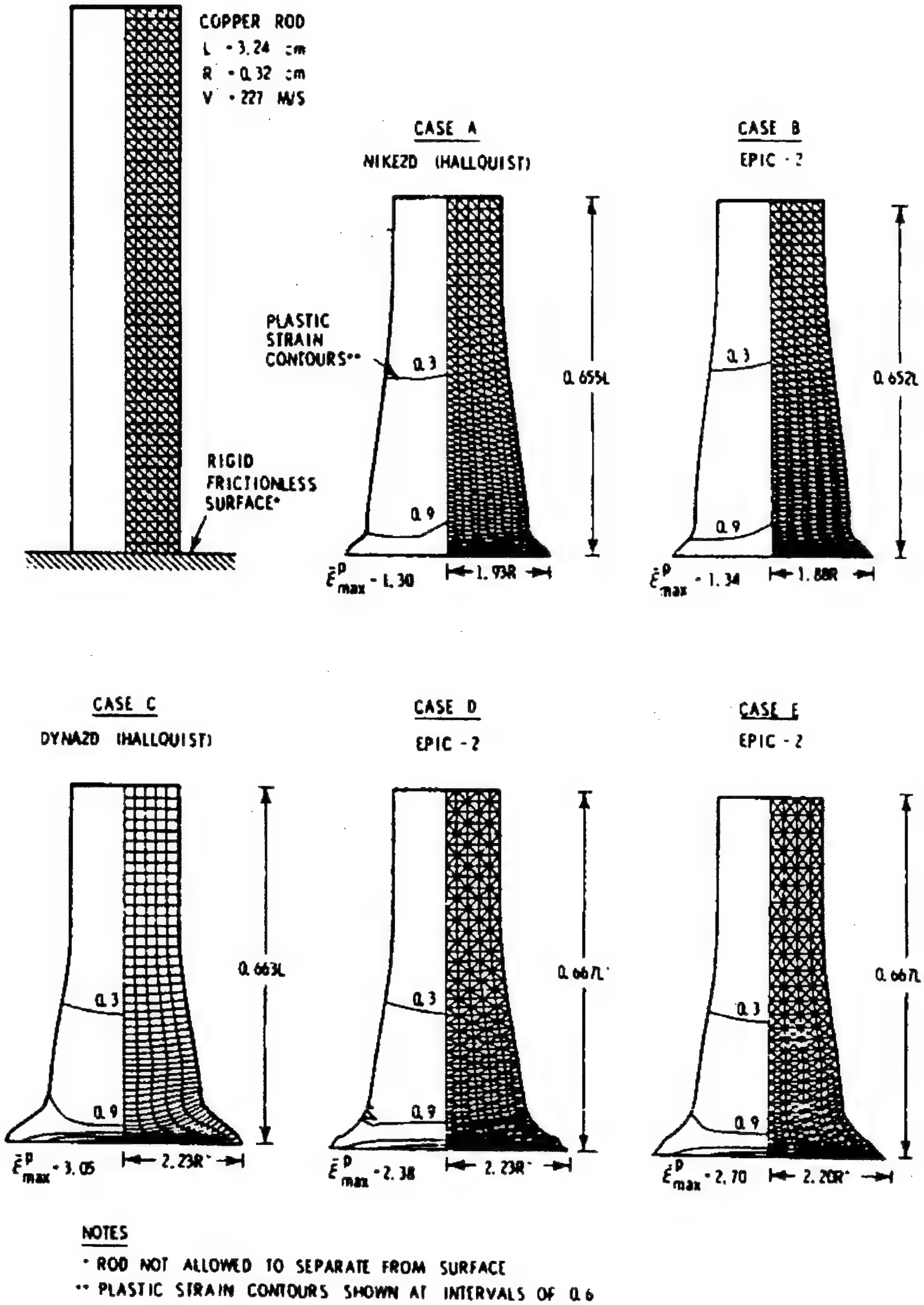
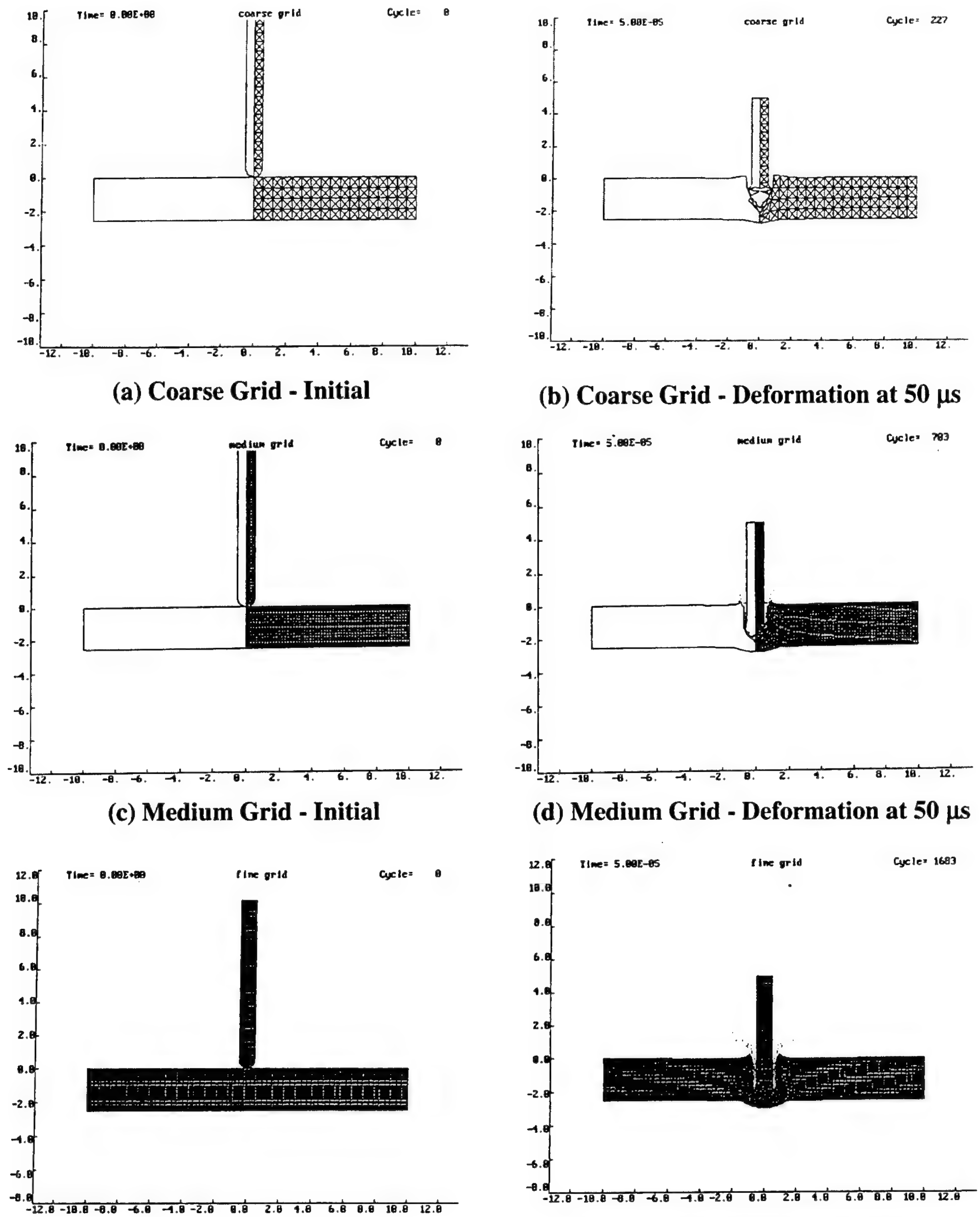


Figure 5. Effects of Element Arrangement on Plastic Strain Distribution [24].



(a) Coarse Grid - Initial

(b) Coarse Grid - Deformation at 50 μs

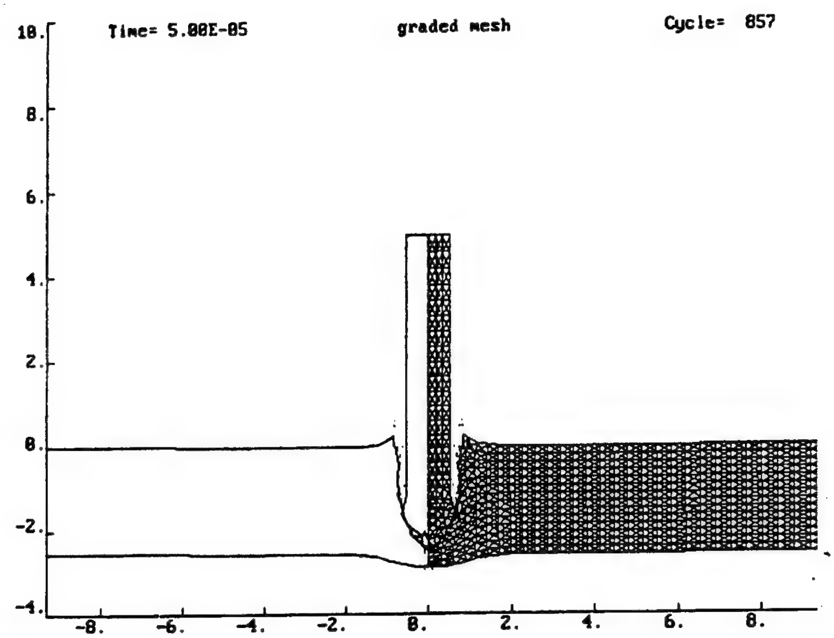
(c) Medium Grid - Initial

(d) Medium Grid - Deformation at 50 μs

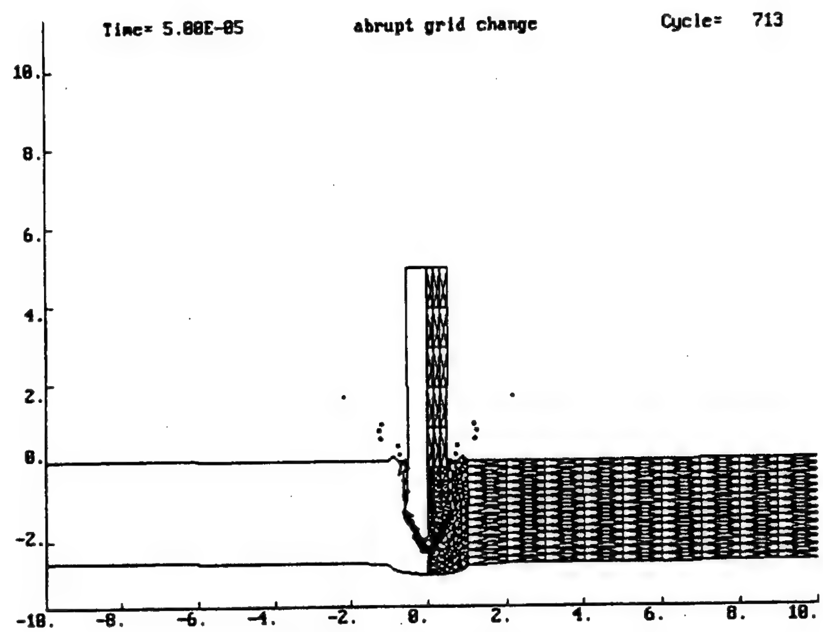
(e) Fine Grid - Initial

(f) Fine Grid - Deformation at 50 μs

Figure 6. Grid Effects on Long-Rod Penetration.



(a) Gradually Changing Mesh.



(b) Abrupt Grid Changes.

Figure 7. Gradual vs. Abrupt Grid Changes.

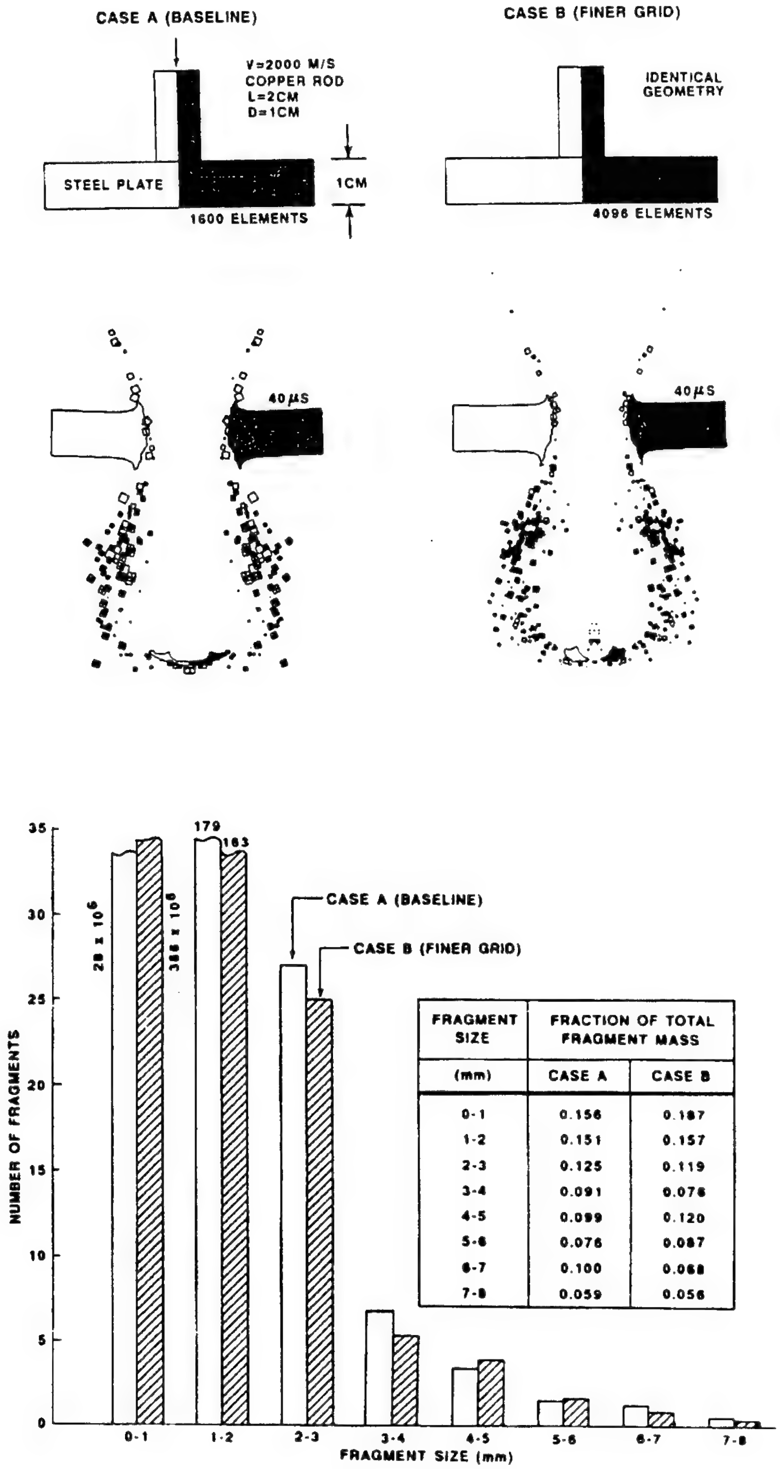
calculation employs failure criteria based on stress wave profiles, results from such coarse calculations will be meaningless.

As spatial resolution is increased by a factor of 2 for 2-D simulations, computer time rises by a factor of 8 for explicit methods [27]. Thus, the resolution used should match the accuracy required. If comparison is to be made with time-resolved pressure, stress, or strain data, if internal failure (such as spall) occurs, fine resolution is required for a meaningful calculation, even though the cost is high. Compromising the accuracy of the calculation to save money in these cases is not justifiable since maximum savings come from not doing the calculation at all. This has the added advantage of not generating meaningless numbers that someone not familiar with the events of the calculation might be tempted to believe. On the other hand, if only global (integral) data are available for comparison (residual masses, lengths, hole sizes, and deformed shapes), a reasonably crude and inexpensive calculation can be done, provided its interpretation is not pushed too far.

It is possible to take advantage of the localized nature of impact problems when setting up computational grids. Typically, the high strain rates and the high pressures, strains, and temperatures that accompany them are confined to a narrow region, or process zone, that extends about three to six striker diameters from the impact interface, depending on striking velocity. Figure 7(a) shows results for a calculation that takes advantage of this information by localizing fine zones within three diameters of the impact interface and then gradually expands element size in regions where, at most, elastic waves will propagate. The result is accuracy comparable to the uniformly gridded case but with considerably fewer elements and, therefore, considerable savings in computer time. Care must be taken not to change element sizes too rapidly, however. A change in element size represents a change in element stiffness even if material properties remain the same. Traveling waves, when encountering this stiffness difference, will act as if an impedance mismatch had occurred. Part of the wave will be reflected, part transmitted. If element-to-element size variation is kept below 10%, acceptable results can generally be achieved. Figure 7(b) shows the negative aspects of drastic changes in element size.

Using a minimum of three continuum elements across a critical dimension such as a rod radius or plate thickness turns out to be a good rule of thumb for Lagrangian calculations. Eulerian calculations require considerably more [28]. Some problems, however, such as hypervelocity impact or self-forging fragment formation, may require much more. These are situations where severe pressure gradients exist and move with time. Also situations such as spall, where material failure occurs due to the interaction of stress waves with geometric boundaries, material interfaces, or each other, will require fine resolution. Zukas et al. [29], studying explosively formed penetrator (EFP) formation and penetration, found that five to six elements through the liner thickness and fine zoning in the target were required to match code calculations with experiments. Melosh et al. [30] modeled dynamic fragmentation on a laboratory scale. They developed a fragmentation model and found good correlation with a wealth of experimental data for the largest fragment size and the fragment size-number distribution, provided that an adequate numerical resolution was used. Resolutions of 12×24 cells (where 12 cells defined target radii, which ranged from 2–12 cm) were used for most calculations. Resolutions of 6×12 and 24×48 cells were also used. All three resolutions gave about the same result. However, substantially finer grids (40×80) were needed to match observed near-surface spallation. Johnson et al. [25] also looked at the effects of grid size on fragment distribution for normal impacts of copper rods at 2 km/s against 1-cm steel plates. Calculations were performed using 1,600 (Case A) and 4,096 elements (Case B). Figure 8 shows the effects of gridding on fragment size distributions for the different grid sizes.

Johnson and Schonhardt [31] investigated the sensitivity of the EPIC-2 and EPIC-3 codes to a number of factors, including gridding for normal and oblique incidence problems. Normal impact calculations for an $L/D = 10$ tungsten rod striking a 2.5-cm steel plate at a velocity of 1.5 km/s were made with 144; 576; 1,296; and 2,304 elements. Oblique impact calculations at 60°, measured from the target normal, were made with 480; 1,920; 4,320; and 7,680 elements. With the exception of the lowest resolution, there was relatively little difference for the higher resolution calculations in terms of residual velocity, residual mass, and hole diameter for the 2-D calculations. Significant increases in CPU times were observed as resolution was enhanced. Similar results were obtained for the 3-D simulations (Figure 9) comparing residual masses, velocities, hole diameters, rotational velocity, and deflection).



FRAGMENT SIZE	FRACTION OF TOTAL FRAGMENT MASS	
(mm)	CASE A	CASE B
0-1	0.156	0.187
1-2	0.151	0.157
2-3	0.125	0.119
3-4	0.091	0.078
4-5	0.099	0.120
5-6	0.076	0.087
6-7	0.100	0.068
7-8	0.059	0.056

Figure 8. Fragment Size Distribution vs. Grid Size [25].

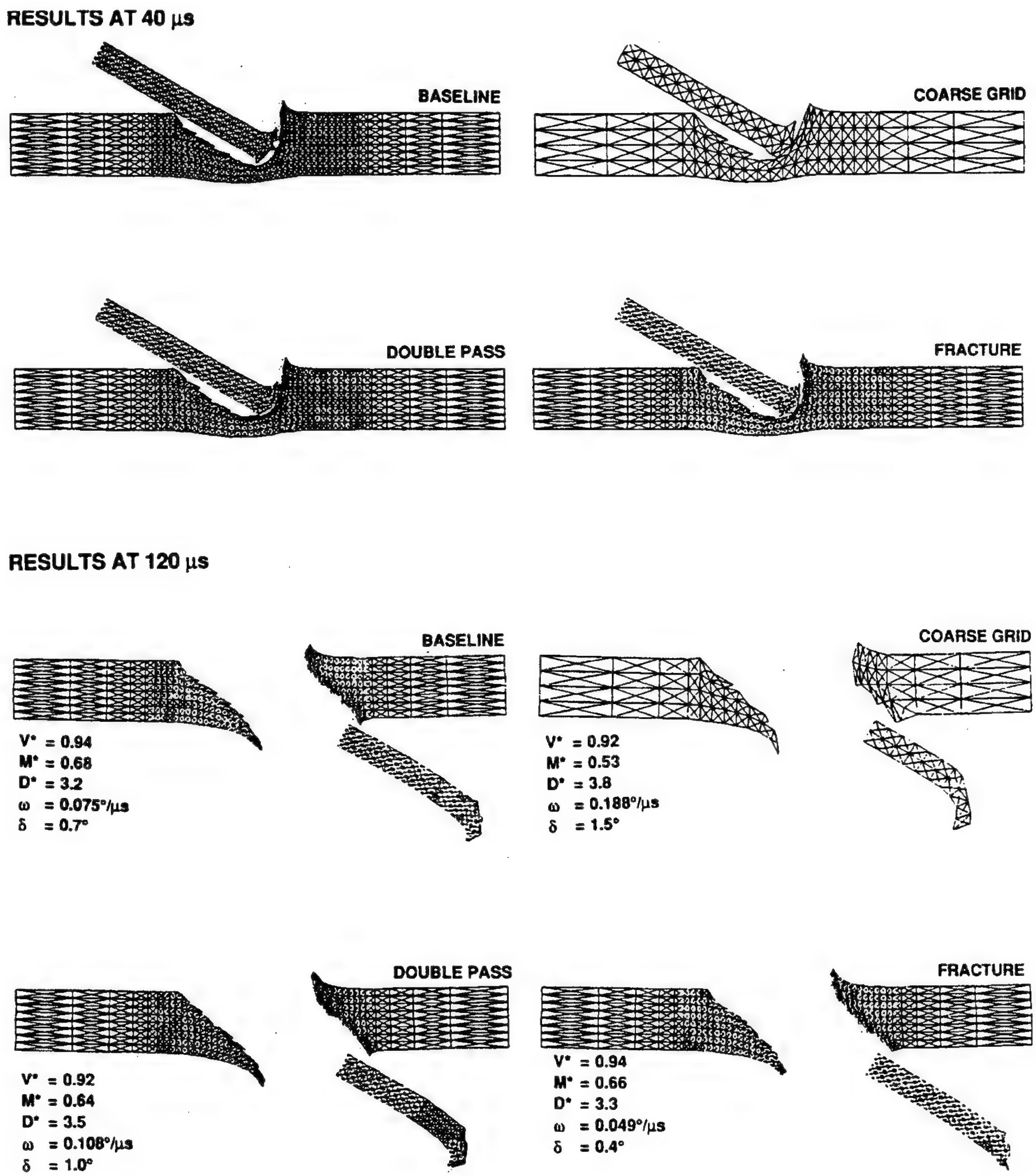


Figure 9. Grid and Contact Surface Effects for Oblique Penetration [31].

Zoning requirements for 2-D and 3-D Eulerian calculations with the CTH code for long-rod penetration problems are considered in Littlefield and Anderson [28].

Guidelines for determining resolution and material modeling for practical engineering problems are given in the report of the National Materials Advisory Board Committee titled "Materials Response to Ultra-High Loading Rates" [16]. The committee recommended an iterative procedure of successive refinements involving computations with existing relatively simple failure descriptions, dynamic material characterization employing relatively simple and standardized techniques, and experimentation to produce useful results for design purposes in many applications. Their report suggests that

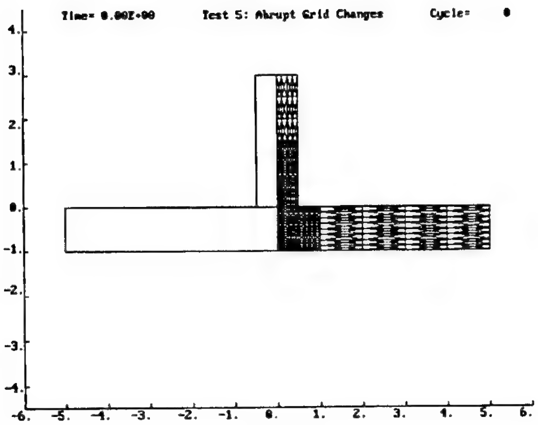
> . . . rough computations, using simple material models with published or even estimated material properties, may be used in conjunction with exploratory test firings to scope an initial design. Comparison of test data with predictions may reveal discrepancies which suggest refinements in the computations or material models, and the need for some material property measurements. Once reasonable agreement has been achieved, another round of computations may then be performed to refine the design. Test firings of this design might use more detailed diagnostic instrumentation. This sequence is iterated, including successively more detail in computational models, material property tests, and ordnance test firings, until a satisfactory design is achieved. In this procedure, unnecessarily detailed computations, material property studies or test firings are minimized; only those details necessary to achieve a satisfactory design are included.

5.4 Abrupt Changes in Meshes. Abrupt grid changes are common in statics calculations. The stress gradient is fixed in space. A grid sufficiently fine for all practical purposes is superimposed over the region. The remainder of the physical body is then modeled with rather large elements to account for the total mass and boundary conditions.

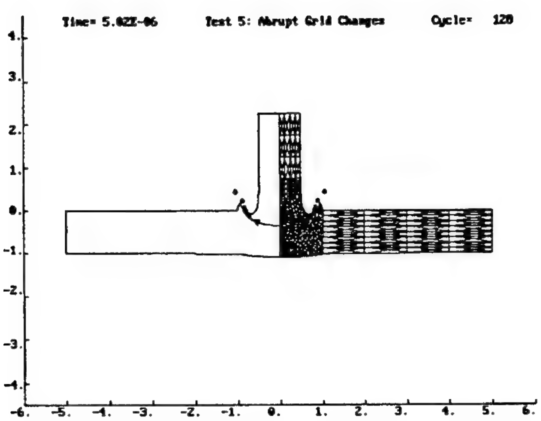
In dynamics calculations, the location of the stress or pressure gradient is a function of time as well as space. It cannot be overemphasized that wave propagation governs the response. Recall from wave propagation theory that stress waves are reflected from material interfaces, geometric boundaries and each other. Partial reflection also occurs at internal points of discontinuity. Chapter 10, in Fried [32], describes this very lucidly, as do Bazant and his colleagues [33–35] for a number of practical systems. A spurious reflection

> . . . occurs when the traveling wave crosses over from a fine mesh region to a coarse mesh region. A given mesh size has a lower limit to the wavelength it can approximate or an upper limit to the frequency it can transmit - the cutoff frequency. When the wave enters the coarse mesh region, some of its high frequency components cannot penetrate and are reflected . . . . As the wave reaches the larger elements, small waves appear, traveling backwards. Also, because of the largest element size, dispersion becomes more pronounced in the form of leading small waves in front of the original one [32].

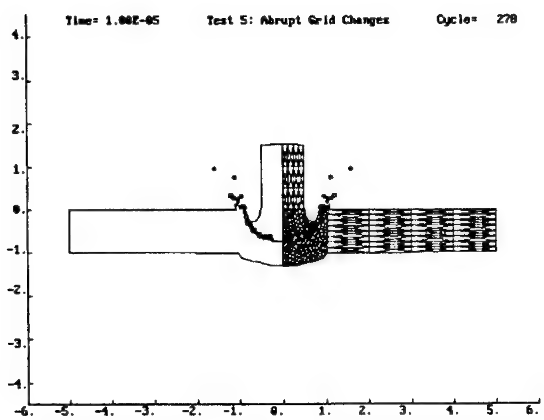
In Fried [32], these points are illustrated with examples of waves in strings. Consider also the following problem, where an L/D = 3 mild-steel projectile impacts an armor-steel target at a velocity of 0.8 km/s with sharp mesh discontinuities in both projectile and target. Figure 10 shows the grid and results at intermediate times. Figure 11 shows the end result. Note that the grid discontinuity has, in effect, predetermined the outcome. The elements are sufficiently large that the distortions in the finely gridded zone are enhanced by reflected high-frequency waves from the fine/coarse element boundary. Compare the results of Figure 12(a) with those of 12(b), where a graduated mesh was used, and Figure 12(c), with a uniform mesh. Keep in mind that, in high-velocity impact problems, the most severe distortions occur within three to six projectile diameters, depending on impact velocity. To the extent possible, this region should be uniformly zoned, with element size gradually increased by no more than 10% (folklore) from there onward.



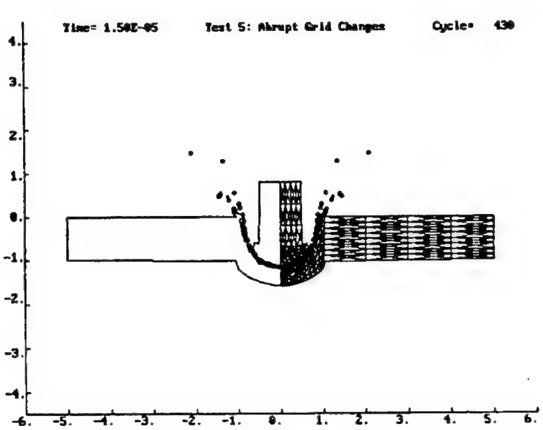
(a) 0 ms



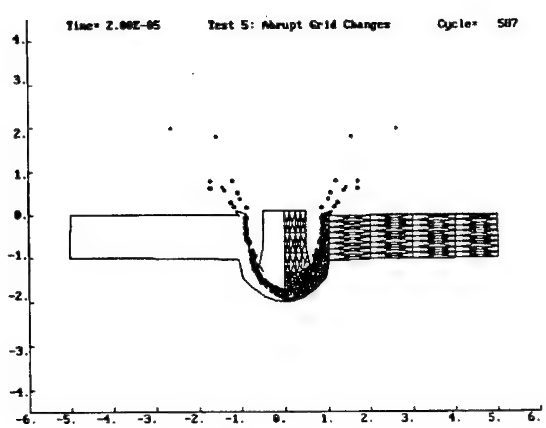
(b) 5 μs



(c) 10 μs



(d) 15 μs



(e) 20 μs

Figure 10. Abrupt Grid Change Effects on Penetration.

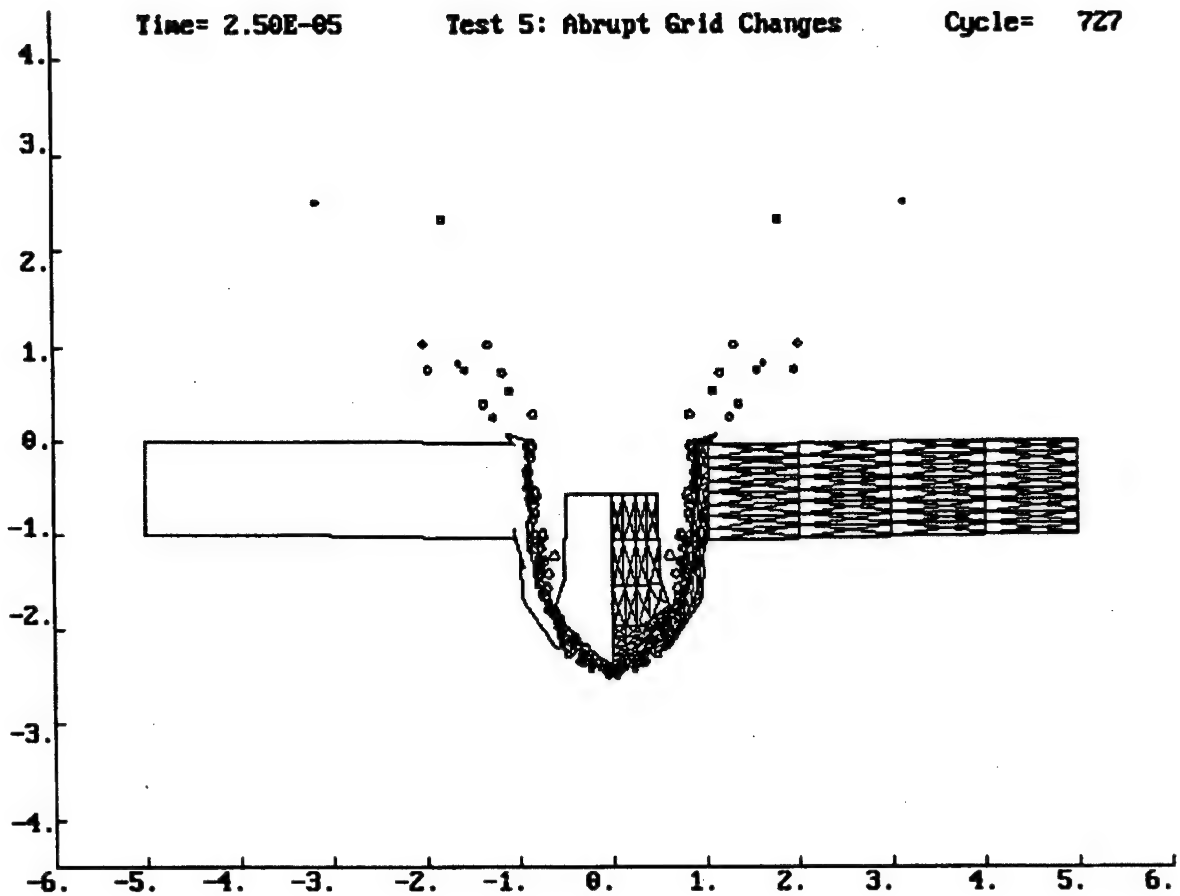


Figure 11. Residual Penetrator and Hole Size in the Presence of an Abrupt Grid Change.

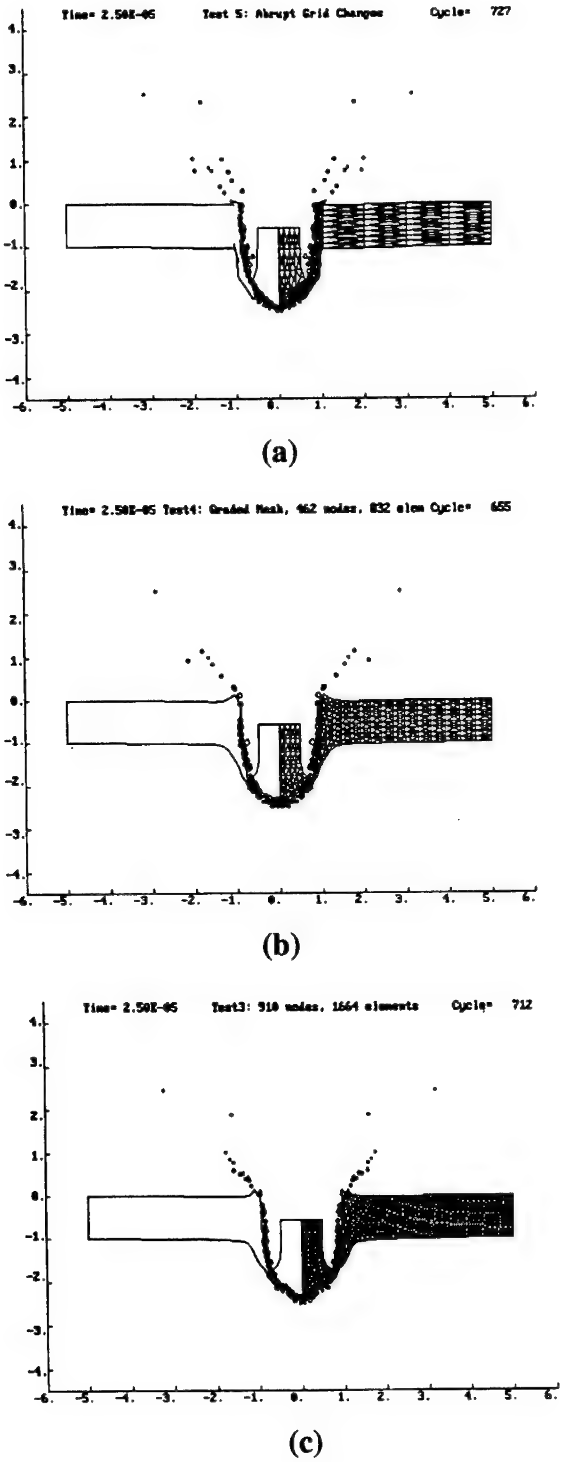


Figure 12. (a) Abrupt Grid Change, (b) Gradual Change in Element Size, and (c) Uniform Meshing.

6. Summary

The causes of disagreement between large-scale code calculations and reality for problems involving fast, transient loading have been discussed. The experience of the analyst is a prime factor in the successful use of commercial codes for problems in dynamics. The analyst needs an appropriate educational background and a keen understanding of the physics and mechanics of the problem being addressed. He/she must also have sufficient experience with numerical techniques and large-scale computations in order to select the appropriate computational tool for the problem and to evaluate the computational results. The currently available commercial codes for dynamics problems are in no way "black boxes" that can be assigned to junior engineers with demands for immediate production. The consequences of inappropriate analyses can range from embarrassment and loss of funding through catastrophic failure of poorly designed structures under service loads, with the liabilities and litigations that inevitably follow.

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7. References

1. Zukas, J. A., and W. P. Walters (editors). *Explosive Effects and Applications.* New York: Springer-Verlag, 1998.

2. Cooper, P. W. *Explosives Engineering.* New York: VCH-Wiley Publishers, 1996.

3. Cooper, P. W, and S. R. Kurowski. *Introduction to the Technology of Explosives.* New York: VCH-Wiley Publishers, 1996.

4. Cheret, R. *Detonation of Condensed Explosives.* New York: Springer-Verlag, 1993.

5. Blazynski, T. Z. (editor). *Explosive Welding, Forming and Compaction.* London: Applied Science Publishers, 1987.

6. Fickett, W., and W. C. Davis. *Detonation.* Berkeley: University of California Press, 1979.

7. Mader, C. L. *Numerical Modeling of Detonation.* Berkeley: University of California Press, 1979.

8. Mader, C. L. *Numerical Modeling of Explosives and Propellants.* Boca Raton: CRC Press, 1997.

9. Herrman, W. "Current Problems in the Finite Difference Solution of Stress Waves." *Nonlinear Waves in Solids, Proceedings of the Workshop at University of Illinois*, Chicago, IL, 21–23 March 1977.

10. Szabo, B. A., and R. L. Actis. "Finite Element Analysis in Professional Practice." *Computer Methods in Applied Mechanics and Engineering*, vol. 133, pp. 209–228, 1996.

11. Utku, S., and R. J. Melosh. "Solution Errors in Finite Element Analysis." *State-of-the-Art Surveys on Finite Element Technology*, A. K. Noor and W. D. Pilkey (editors), New York: ASME, 1983.

12. Melosh, R. J., and S. Utku. "Principles for Design of Finite Element Meshes." *State-of-the-Art Surveys on Finite Element Technology*, A. K. Noor and W. D. Pilkey (editors), New York: ASME, 1983.

13. Meyer, C. (editor). *Finite Element Idealization.* New York: ASCE, 1989.

14. MacNeal, R. H. *Finite Elements: Their Design and Performance.* New York: Marcel Dekker, 1994.

15. Morris, A. J., and R. Vignjevic. "Consistent Finite Element Structural Analysis and Error Control." *Computer Methods in Applied Mechanics and Engineering*, vol. 140, pp. 87–108, 1997.

16. National Materials Advisory Board. "Materials Response to Ultra-High Loading Rates." NMAB-356, Washington, DC, 1980.

17. Belytschko, T., and R. J. R. Hughes. *Computational Methods for Transient Analysis*. New York: Elsevier Science Publishing Co, Third Printing, 1992.

18. Donea, J. (editor). *Advanced Structural Dynamics*. London: Applied Science Publishers, 1978.

19. Zienkiewicz, O. C. "Finite Elements in the Time Domain." *State-of-the-Art Surveys on Finite Element Technology*, A. K. Noor and W. D. Pilkey (editors), New York: ASME, 1983.

20. Creighton, B. "Numerical Resolution Calculation for Elastic-Plastic Impact Problems." BRL-MR-3418, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1984.

21. Skalak, R. "Longitudinal Impact of a Semi-Infinite Circular Elastic Bar." *Journal of Applied Mechanics*, Transactions ASME, vol. 24, pp. 59–63, 1957.

22. Zukas, J. A. "Some Problems With the EPIC-2 Code." Internal Memorandum IMR 647, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1979.

23. Nagtegaal, J. C., D. M. Parks, and J. R. Rice. "On Numerically Accurate Finite Element Solutions in the Fully Plastic Range." *Computer Methods in Applied Mechanics and Engineering*, vol. 4, pp. 153–178, 1974.

24. Johnson G. R. "Recent Developments and Analyses Associated With the EPIC-2 and EPIC-3 Codes." *Advances in Aerospace Structures and Materials*, S. S. Wang and W. J. Renton (editors), vol. AD-01, New York: ASME, 1981.

25. Johnson, G. R., R. A. Stryk, T. J. Holmquist, and O A. Souka. "Recent EPIC Code Developments for High Velocity Impact: 3D Element Arrangements and 2D Fragment Distributions." *International Journal of Impact Engineering*, vol. 10, pp. 281–294, 1990.

26. Hohler, V., E. Schneider, A. J. Stilp, and R. Tham. "Length and Velocity Reduction of High Density Rods Perforating Mild Steel and Armor Steel Plates." *Proceedings of the 4th International Symposium on Ballistics*, Monterey, CA, 1978.

27. Zukas, J. A., and K. D. Kimsey. "Supercomputing and Computational Penetration Mechanics." *Computational Aspects of Contact, Impact and Penetration*, R. F. Kulak and L. E. Schwer (editors), Lausanne, Switzerland: Elmepress International, 1991.

28. Littlefield, D. L., and C. E. Anderson, Jr. "A Study of Zoning Requirements for 2-D and 3-D Long-Rod Penetration." *American Institute of Physics*, pp. 1131–1134, 1996.

29. Zukas, J. A., C. A. Weickert, and P. J. Gallagher. "Numerical Simulation of Penetration by Explosively-Formed Projectiles." *Propellants, Explosives and Pyrotechnics*, vol. 18, pp. 259–263, 1993.

30. Melosh, H. J., E. V. Ryan, and E. Asphaug. "Dynamic Fragmentation in Impacts: Hydrocode Simulation in Laboratory Impacts." *Journal of Geophysical Research*, vol. 97, no. E9, pp. 14735–14759, 1992.

31. Johnson, G. R., and J. A. Schonhardt. "Some Parametric Sensitivity Analyses for High Velocity Impact Computations." *Nuclear Engineering and Design*, vol. 138, pp. 75–91, 1992.

32. Fried, I. *Numerical Solution of Differential Equations*. New York: Academic Press, 1979.

33. Bazant, Z. P. "Spurious Reflection of Elastic Waves in Non-Uniform Finite Element Grids." *Computer Methods in Applied Mechanics and Engineering*, vol. 16, pp. 91–100, 1978.

34. Bazant, Z. P., and Z. Celep. "Spurious Reflection of Elastic Waves in Nonuniform Meshes of Constant and Linear Strain Finite Elements." *Computer and Structures*, vol. 15, pp. 451–459, 1982.

35. Celep, Z., and Z. P. Bazant. "Spurious Reflection of Elastic Waves Due to Gradually Changing Finite Element Size." *International Journal for Numerical Methods in Engineering*, vol. 19, no. 5, pp. 631–646, 1983.

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13. ABSTRACT *(Maximum 200 words)*

The use of finite-difference and finite-element computer codes to solve problems involving fast, transient loading is commonplace. A large number of commercial codes exist and are applied to problems ranging from fairly low to extremely high damage levels (e.g., design of containment structures to mitigate effects of industrial accidents; protection of buildings and people from blast and impact loading; foreign-object impact damage; and design of space structures to withstand impacts of small particles moving at hypervelocity, a case where the pressures generated exceed material strength by an order of magnitude). But, what happens if code predictions do not correspond with reality? This report discusses various factors related to the computational mesh that can lead to disagreement between computations and experience. Subsequent reports will focus on problems associated with contact surfaces and material transport algorithms, constitutive models, and the use of material data at strain rates inappropriate to the problem. It is limited to problems involving fast, transient loading, which can be addressed by commercial finite-difference and finite-element computer codes.

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